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Life cycle energy, emissions and cost inventory of power generation technologies in Singapore

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Abstract

Singapore is one of the most industrialised and urbanised economies in South-East Asia. Power supply is an important sub-system in its economy and heavily reliant on imported oil and natural gas. Due to its geographical area, clean/renewable energy sources for power generation are limited. At the same time, in its deregulated electricity market, the adoption of clean/renewable based power generation technology may be hindered by a market pricing mechanism that does not reflect externality costs. For a sustainable power supply, there is a need to change the conventional appraisal techniques. Life cycle assessment (LCA) and life cycle cost analysis (LCCA) are good tools to quantify environmental impacts and economic implications. LCA and LCCA are performed for centralised and distributed power generation technologies in Singapore, namely, oil and Orimulsion-fired steam turbines, natural gas-fired combined cycle plant, solar PV and fuel cell systems. A life cycle energy, emission and cost inventory is established. The results are discussed from the perspectives of fuel security, environmental protection and cost effectiveness of future power generation strategies for Singapore.

Keywords: Life cycle assessment; Life cycle cost analysis; Singapore; Electricity

Contents

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1. Introduction

Singapore is one of the most industrialised and urbanised economies in South-East Asia. In 2003, the country's gross domestic product was 159 billion Singapore dollars[1] (S$) [1]. Power supply is an important sub-system in the national economy. Singapore is almost totally reliant on imported oil and natural gas for power generation. Table 1 provides an overview of the Singapore power sector. Until 1992, oil was the only fuel used for power generation. To diversify its energy source, Singapore started using natural gas for power generation in 1992. In 1993, natural gas accounted for about 16% of the total power generation [2]. In recent years, the use of natural gas for power generation has grown at a rapid rate and in 2003 about 61% of the electricity was generated from natural gas [3]. Most of the country's installed power plants are steam turbines and its first combined cycle plant was commissioned in 1997 [4]. In 2001, the first[2] cogeneration plant commenced operation [5]. Due to market competition in the deregulated electricity market, new combined cycle plants are being constructed [6] and existing steam turbine plants are being converted into combined cycle plants [4]. One of the power companies is converting its fuel oil-fired steam turbines to use cheaper Orimulsion[3] fuel to compete in the deregulated electricity market [7].

Due to Singapore's geographical area, renewable energy sources for power generation are limited. The most promising domestic source of renewable energy is solar radiation. The country receives an annual solar radiation of 1635 kWh/m^2 [14]. However, only distributed solar photovoltaic (PV) power generation systems can be installed due to constraints in space. As a demonstration project, a 8.9 kW$_p$ grid connected solar PV system[4] has been operating since 2002 [15]. There are also a few other solar PV installations with battery storage [16]. The Singapore government encourages innovationsin the area of clean energy and supports R&D and test-bedding activities on clean energy technologies. Under the Singapore Initiative in New Energy Technology program

[1]US$1 = S$ 1.674 as on 19 October 2004.

[2]It is the first privately developed independent power producer and largest cogeneration plant (815 MW with optimal output of 650 MW$_e$ and 550 tonnes of steam per hour) in Singapore [5].

[3]Orimulsion is a liquid fossil fuel consisting of an emulsion of 70% bitumen (a naturally occurring heavy petroleum material) from the Orinoco region of Venezuela, 30% water, and a small amount of surfactant [13].

[4]It comprises 2.7 kW$_p$ mono-crystalline, 3.066 kW$_p$ poly-crystalline and 3.12 kW$_p$ CIS thin film [15].

Table 1
Overview of Singapore power sector

Data description	Year	Values	Remarks
Installed capacity [8]	2003	8919 MW	53% steam turbine, 30%combined cycle and the rest are gas turbines and waste incineration plants
Peak power demand [3]	2003	5139 MW	
Annual average growth rate of peak power demand [3]	1998–2003	3.6%	
Electricity consumption [9]	2003	32 TWh	43% industrial sector, 37% commercial sector and 20%, residential sector [9] 61% natural gas, 35%fuel oil and 4%refuse incineration, Diesel, synthesis gas and Orimulsion oil [3]
Annual average growth rate	1993–1998	8.7%	
of electricity consumption [9]	1998–2003	4.2%	
Annual electricity demand forecast [10]	2003–2013	3–5%	
Transmission and distribution (T&D) losses [11]	2002	4%	About 22,544 km underground cable network for electricity T&D [12]
CO2 emission	2003	17 million tones	Estimated from power generation mix [3] using an efficiency of 52% for gas-fired combined cycle plant and 36% for oil-fired steam turbine plant

(SINERGY), a S$50 million fund has also been established [17]. A test-bedding project is currently underway in a multi-storey car park, where the lights are powered by fuel cells using hydrogen produced by reforming of natural gas [18].

Increasing concerns on global warming demand a steep reduction in CO_2 emissions from the power sector. Depletion of fossil fuels points to the need for alternative clean/renewable sources of energy for power generation. In today's deregulated electricity market, the power sector faces heightened competition and market demands for cost-effective power generation. It is common in the energy sector that market price does not reflect the *full costs*, which include environmental externalities [19]. Thus, the current market pricing mechanism is one of the factors hindering the adoption of clean/renewable energy technologies. Considering the challenges of sustainable power generation, it is necessary to adopt changes to conventional appraisal. To address current energy-environmental issues, we must go beyond conventional economic appraisal techniques.

This needs an effective evaluation tool that takes into account the long-term implication of power generation. Such an evaluation tool is based on the life cycle concept, which is a cradle-to-grave approach to analyse an energy system in its entire life cycle. The tools chosen are life cycle assessment (LCA) and life cycle cost analysis (LCCA). LCA is an effective tool to pinpoint environmental implications although it does not account for economic implications. LCCA provides effective evaluation to pinpoint cost effective alternatives but it does not account for environmental impact of such alternatives. LCA and LCCA together can pinpoint the cost-effective power generation options with greatest potential for emission reduction and minimisation of fossil energy use.

LCA and LCCA are performed for five power generation technologies in Singapore, namely, 250 MW oil-fired steam turbine plant, 367.5 MW natural gas-fired combined cycle plant, 250 MW Orimulsion-fired steam turbine plant, 2.7 kW_p solar PV and 5 kW proton exchange membrane fuel cell (PEMFC). The former three technologies are centralised power generation systems while the latter two are distributed power generation (DG) systems. The aim of this paper is to compare the selected five power generation technologies from the perspectives of their life cycle primary energy use, global warming potential (GWP) and cost. These three criteria are considered as indicators of fuel security, environmental protection and economic growth, respectively. The results are critically analysed in the context of future power generation strategies for Singapore.

2. LCA and LCCA methodology

The goal of a LCA is to quantify non-renewable (fossil) primary energy use and GWP in electricity generation while the LCCA aims to estimate its life cycle cost. For centralised power generation technologies, the functional unit is defined as one kWh of electricity delivered to the grid. Thus, establishment of transmission and distribution (T&D) network is not included. For DG, the functional unit is one kWh of electricity generated. It is assumed that the generated electricity from DG would be consumed locally and thus no T&D losses will occur.

In previous papers [20,21], the authors have elucidated the LCA and LCCA methodologies. In LCA, the life cycle of power generation technology is considered in three phases viz. construction, operation and decommissioning. In the construction phase, production of plant equipment and on-site construction are included. In the operational phase, fuel use during the entire operational lifetime and upstream process of fuel productions are included. In the decommissioning phase, demolition of energy system, disposal and recycling of materials are included. The life cycle primary energy use is estimated as the sum of the energy consumed in three life cycle phases, which includes energy consumed in exploration, extraction, processing, manufacturing, decommissioning and disposal of all the materials associated with the power generation system. By tracing the primary sources of energy, three major greenhouse gases (GHG), namely, CO_2, CH_4 and N_2O, are estimated. The GHG are classified under global warming category and the GWP per functional unit is calculated in CO_2 equivalents.

In LCCA, costs are grouped into three categories similar to the three phases in LCA. Costs involved in the construction phase are considered as capital costs, which include the initial capital expense for equipment and installation. The capital costs are accounted with an annual interest rate of 5% payable over the lifetime of the energy system. Costs incurred during the operational phase are operation and maintenance (O&M) costs, and fuel costs. They are projected for the entire operational lifetime with an annual price escalation of 2% and reduced to their present value using discounting techniques with a discount rate[5] of 1%. In the decommissioning phase, costs are incurred in demolition and disposal of the system while the equipment can have some salvage value. The net costs from the decommissioning phase are accounted with a discount rate of 1%. Life cycle cost (LCC) is

[5]The discount rate reflects either the effect of the real earning power of money invested over time or the effects of inflation.

estimated as the sum of the costs involved in the three life cycle phases. Cost of electricity generation per functional unit (kWh-$_e$) is calculated from LCC.

3. LCA and LCCA results

3.1. Oil-fired steam turbine power plant

Operating parameters of the 250 MW oil-fired steam turbine plant are given in Table 2. The details of life cycle boundaries and data sources are described in Kannan et al. [20]. The life cycle primary energy use and GWP of electricity generation from the steam turbine plant are 10.89 MJ_t/kWh_e and 854 g-CO_2/kWh_e, respectively. The construction phase, upstream processes of fuel oil production and its transportation account for 9% and 12% of the life cycle energy and GWP, respectively. In GWP, CO_2 contributes for 96.6% while CH_4 and N_2O accounts for 2.9% and 0.5%, respectively.

For the LCCA, a capital cost of S$ 1 million perMWand an annual O&M cost of 4% of the capital cost are used. For the fuel cost, high sulphur fuel oil (HSFO) price of S$ 325 per tonne is used based on Singapore's fuel oil price in January 2005 [22]. The life cycle cost of electricity generation from the steam turbine plant is calculated as 10.65 ¢ per kWh_e. Fuel use accounts for about 83% of this cost while capital and O&M costs account for 11% and 6%, respectively. The cost of electricity generation primarily depends on the fuel oil price while the fuel oil consumption varies with operating efficiency of the power plant. Therefore, the cost of electricity generation is estimated for a range of fuel oil price and net plant efficiency and is shown in Fig. 1.

3.2. Natural gas-fired combined cycle plant

The selected 367.5 MW natural gas-fired combined cycle plant has been operating in Singapore since 2001 and its operating parameters are given in Table 2. The life cycle primary energy use and GWP of electricity generation from the combined cycle plant are 7.79 MJ_t/kWh_e and 473 g-CO_2/kWh_e, respectively. The upstream processes of natural gas

Table 2
Operating parameters of selected power generation technologies in Singapore

Description	Oil-fired steam turbine	Orimulsion-fired steam turbine	Gas-fired combined cycle	Mono-crystalline solar PV	Gas based PEM fuel cell
Installed capacity	250 MW	250 MW	367.5 MW	2.7 kW_p	5 kW
Plant net efficiency	36%	33%	50%	8.71%[a]	26%
Annual load factor	80%	80%	80%	–	70%
Annual power generation (kWh_e)	1728 million	1728 million	2352 million	2630[a]	30.240
Plant lifetime (years)	25	25	25	25	20[b]

[a]Source: Building Construction Authority [15].

[b]Source: Stationary Fuel Cells Operating Info, http://www.fuelcells.org/StationaryOperating.pdf (December 2002).

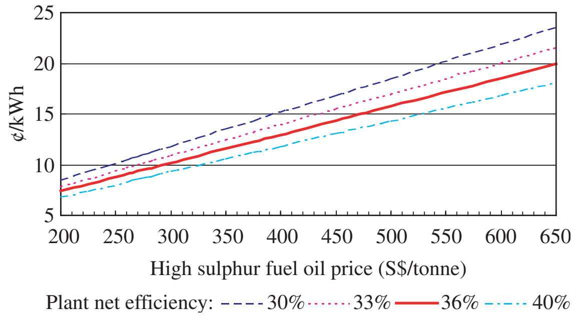

Fig. 1. Life cycle cost of electricity generation from oil-fired steam turbine plant.

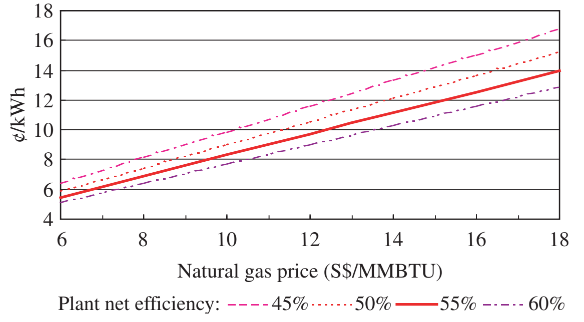

Fig. 2. Life cycle cost of electricity generation from oil-fired steam turbine plant.

production account for 7.2% of the life cycle energy use and 11.7% of the GWP. The transportation of natural gas accounts for 3.3% of the GWP, mainly due to venting of natural gas (also see Kannan et al. [21]).

For the LCCA of combined cycle plant, a capital cost of S$ 0.8 million per MW and an annual O&M cost of 3% of the capital cost are used. In Singapore, the natural gas price is pegged to HSFO price. The natural gas imported from Malaysia is based on 107% of the HSFO, while that from Indonesia costs 115% of the HSFO price [23]. A weighted average of 113% of HSFO prices is used as 80% of the natural gas is imported from Indonesia [3] Therefore, natural gas price of S$ 8.70 per MMBTU is used in the LCCA. The cost of electricity generation from the combined cycle plant is calculated as 8.05 ¢ per kWh_e. The cost of electricity generation is also estimated for a range of natural gas prices and net operating efficiency and is presented in Fig. 2.

3.3. Orimulsion-fired steam turbine power plant

One of the power companies is converting three of its 250 MW fuel oil-fired steam turbines to use Orimulsion fuel by 2005 [7]. A streamlined LCA is performed for a hypothetical 250 MW Orimulsion-fired steam turbine plant. Its operational parameters are assumed to be the same as those of the fuel oil-fired plant and a net efficiency of 33% is used. An efficiency value lower than that of the oil-fired steam turbine is used because the Orimulsion-fired plant uses additional pollution control equipment viz. flue gas

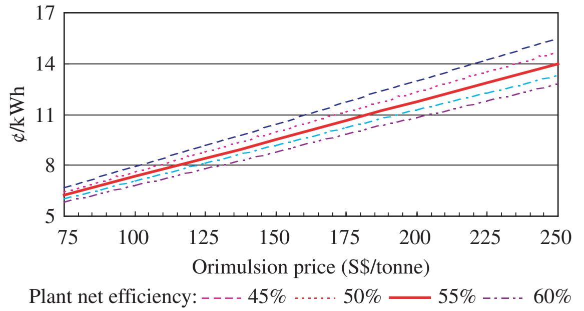

Fig. 3. Life cycle cost of electricity generation from Orimulsion-fired steam turbine plant.

desulphurisation system, NO_x control system and electrostatic precipitator and it would require additional auxiliary power [25]. The high moisture content of the Orimulsion fuel could also limit the flame temperature [24].

The LCA of steam turbine and combined cycle plant show that the energy use and emissions are insignificant in the construction and decommissioning phases. Thus, for this LCA, only the energy use and emissions from the upstream processes and transportations of Orimulsion fuel are taken into account. Energy use and emissions from the extraction and treatment of Orimulsion fuel is adopted from Berry et al. [24]. The annual Orimulsion fuel demand is estimated based on its lower heating value of 28 MJ/kg. The CO_2 emission factor of the Orimulsion fuel is estimated as 78.57 t-CO_2/TJ based on its carbon content [13]. The N_2O emission in the operational phase is assumed as in the fuel oil-fired steam turbine plant.

The life cycle primary energy use and GWP of electricity generation from the Orimulsion-fired steam turbine is estimated as 12.38 MJ_t/kWh_e and 975 g-CO2/kWh_e, respectively. The energy use and GWP from the upstream process of Orimulsion fuel is only about 4%. The transportation of Orimulsion fuel accounted for 7% of the life cycle energy and emissions because of its 30% water content and the fact that it would be imported from Venezuela.

For the LCCA of Orimulsion-fired steam turbine, the capital cost is adopted from the oil-fired steam turbine plant. However, additional costs involved in modification of oil-fired plant into Orimulsion-fired plant are included [25]. Thus, a capital cost of S$ 1.4 million and an annual O&M cost of 5% of the capital cost are used. The Orimulsion fuel price is about 38% of the fuel oil price on weight basis [25,26]. On energy basis, it is about 56% of the fuel oil price. Thus, an Orimulsion fuel price of S$ 125 per tonne is used in the LCCA. The cost of electricity generation is calculated as 7.99 ¢ per kWh_e. Fuel use accounts for about 69% of this cost while capital and O&M costs account for 18% and 13%, respectively. The variation of the cost of electricity with respect to the plant efficiency and Orimulsion fuel price is shown in Fig. 3.

3.4. Solar PV system

The 2.7 kW_p mono-crystalline solar PV system has been operating since 2002 [15]. It is installed on a building rooftop and connected to the grid. It is installed in such a way that the generated electricity is firstly used for the building load. Since electricity generated from

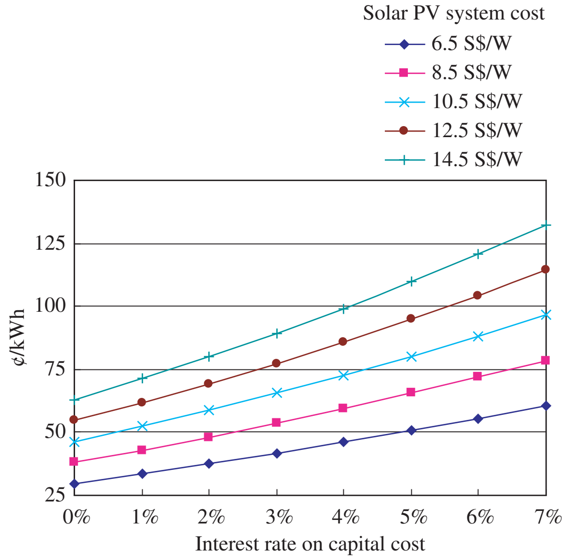

Fig. 4. Life cycle cost of electricity generation from solar PV system.

the solar PV system is a fraction of the building's total power requirement, all the generated electricity is used locally, and hardly any electricity is exported to the grid. The operating parameters of the solar PV system are given in Table 2.

For the LCA, manufacturing of solar PV modules [27], supporting structures, inverters and their accessories [28] are included in the system boundary. For the calculations of life cycle energy use and GWP, an annual electricity generation of 2630 kWhe is used [15]. The life cycle primary energy use and GWP of electricity generation from the solar PV system are estimated as 2.91 MJ_t/kWh_e and 217 $g\text{-}CO_2/kWh_e$, respectively. The manufacturing of PV module accounted for about 81% of the life cycle energy use and the GWP while the supporting structures accounted for 10%.

For the LCCA, current market prices of solar PV module and inverter of 8.5 and 1.4 S$/$W_p$ are used [29]. The costs of supporting structure, installation and commissioning are adopted from the actual cost of the solar PV project [15]. A specific capital cost of 12.6 S$/$W_p$ is used in the LCCA. Though no exclusive O&M is required for the solar PV systems, a labour cost for fortnightly cleaning of the solar PV modules is included in the LCCA. This works out to about 0.15% of the capital cost. The cost of electricity generation from the solar PV system is calculated as 94.53 ¢ per kWh_e. The capital cost accounted for 96% of the life cycle cost. The capital cost could vary with size of the solar PV systems. Perhaps it would be about 10–11 S$/$W_p$ for a system size larger than 100 kW_p. The cost of electricity also depends on the interest on capital investment. A cost scenario for a range of solar PV system cost and interest rate is shown in Fig. 4.

3.5. PEMFC

A hypothetical 5 kW natural gas based PEMFC with onboard reformer is considered for this study. The PEMFC is chosen because it has been installed as a demonstration project

in Singapore [18]. The operating parameters of the PEMFC are given in Table 2. The LCA boundary is the same as that for the natural gas-fired combined cycle plant. Energy and emission data for production of PEMFC are adopted from Pehnt [30]. For the electricity generation from the PEMFC system, the life cycle energy use is 14.93 MJ_t/kWh_e and its distribution is not very different from that of the natural gas-fired combined cycle plant (see Section 3.2). The GWP is 899 g-CO_2/kWh_e, which is slightly lower than the GWP from a natural gas-fired combined cycle plant with the same operating efficiency because there is no N2O emission from the operation of a fuel cell.

For the LCCA, the capital cost of PEMFC, the average fuel cell price of S$ 7600 per kW is used [31] while the balance of the system is adopted from the solar PV system. The cost of electricity generation is estimated to be 28.21 ¢ per kWhe for a natural gas price of S$ 8.70 per MMBTU. The capital cost accounts for 48% while the fuel cost accounts for 45%.

4. Discussions

To compare electricity from centralised plants and DG systems, energy losses in T&D and the cost involved in establishment of T&D network should be added to the centralised power generation technologies. In Singapore, T&D losses is about 4% [11] while the low-tension transmission cost is 5.53 cents/kWh [32]. These values are added to the centralised power generation technologies. Table 3 gives a summary of the life cycle primary energy use, GWP and the cost of electricity from the selected technologies. It is difficult to decide which option is the best. From the perspectives of fuel security and protection of environment, the solar PV based power generation appears to be the best whereas the Solar PV system cost natural gas and Orimulsion-based power generation are the best from the economic perspective. Hence, making a wise choice depends on the national policy objectives.

4.1. Natural gas

The natural gas-fired combined cycle plant is a cost effective source of power generation and its GWP is also relatively low. Hence, a shift towards the natural gas based combined cycle plant would be a good choice for Singapore. However, fuel security poses a big challenge with reliance on a single fuel from three[6] sources of supply. In the year 2002 and 2004, Singapore experienced two major blackouts caused by an interruption[7] in the natural gas supply pipeline [33,34]. The blackout was short-lived and power supply was restored by switching over to fuel oil. Re-occurrence of any such an interruption may be more critical, especially if it could be due to any accident or political vulnerability. Risks of fuel security cannot be avoided in Singapore, as almost 100% of its fuel needs are imported. However, reliance on a single source of natural gas supply would pose additional risks to the reliability of entire power supply. Unlike fuel oil, natural gas cannot be stored in large volumes and an alternative supplier cannot be sought out in a short time because of the

[6]Currently, natural gas is imported from Indonesia via two submarine pipelines and from Malaysia via one pipeline.

[7]In 2002, the emergency shutdown valves were activated and disrupted the natural gas supply [33]. In 2004, it was due to failure of a pressure regulating valve [34].

Table 3
Life cycle energy, emission and cost inventory of electricity from selected technologies in Singapore

Power generation systems	Net (LHV) efficiency (%)	Life cycle primary energy use (MJ_t/kWh_e)	Life cycle GWP (g-CO_2/kWh_e)	Life cycle cost (¢/kWh_e)
Oil-fired steam turbine[a]	36	11.32	889	16.18[b,c]
Gas-fired combined cycle[a]	50	8.10	493	13.58[b,d]
Orimulsion-fired steam turbine[a]	33	12.88	1014	13.52[b,e]
Solar PV (mono-crystalline)	8.7	2.91	217	94.53[f]
Gas based PEMFC	26	14.93	899	28.21[d,g]

[a]4%T&D losses included.
[b]5.53 ¢/kWh included for T&D network.
[c]Fuel oil price of S$ 325 per tonne.
[d]Natural gas price of S$ 8.7 per MMBTU.
[e]Orimulsion fuel price of S$ 125 per tonne.
[f]Solar PV system price of S$ 12,600 per kW_p.
[g]PEMFC price of S$ 7600 per kW.

limitations in infrastructure. One diversification option would be to import liquefied natural gas (LNG). Singapore is currently conducting a feasibility study for a LNG import terminal [35]. The economics of using LNG is still unclear although it is likely to be more expensive than piped natural gas [36]. Therefore, shifting to 100% natural gas based power generation cannot be the best choice even if natural gas is a cleaner and cheaper (due to higher efficiency) fuel for power generation.

4.2. *Fuel oil/Orimulsion*

The next fuel option for power generation is fuel oil, which has a higher GWP while the cost and energy use are intermediate (see Table 3). From the fuel security perspective, availability of fuel oil is abundant considering that Singapore is a refining and petrochemical hub.

Another alternative is Orimulsion based power generation. As far as electricity generation from Orimulsion fuel is concerned, its cost is comparable with electricity from natural gas-fired combined cycle plant. However, its GWP is the highest among the selected technologies and more than two times higher than natural gas based power generation. While considering the increasing international pressure for reduction of GHG emission, use of Orimulsion would significantly increase the overall emission from power sector. Since 2000, emissions from the power sector have been decreasing due to greater use of natural gas. However, this trend would be reversed if Orimulsion fuel becomes a significant part of the power generation mix. As far as fuel availability is concerned, its supply is also limited to a single supplier, Bitumenes Orinoco S.A (Bitor), the national oil company of Venezuela.

In order to consider fuel security, environmental protection and economic efficiency, a balance between natural gas and fuel oil/Orimulsion has to be made. In either case, it is impossible to keep away from oil price shocks or political vulnerabilities. Hence, alternative sources of power generation are inevitable.

4.3. Solar PV

Power generation from the solar PV system uses less than one-fourth of the life cycle primary energy of the oil-fired plant and 36% of the natural gas-fired plant. The GWP from solar PV system is less than one-fourth/fifth of the fuel oil/Orimulsion-fired plant and just half of the natural gas-fired combined cycle plant. Therefore, from either the fuel security or GWP perspective, solar PV is a good alternative. However, the cost of electricity generation from the solar PV system is about 5 to 7 times higher than the oil/Orimulsion/natural gas based power generation. Therefore, in the short-term, solar PV based power generation is not economically the best choice. However, the cost of solar PV systems is likely to continue decreasing in the near future [29]. Recently, oil prices have surged to a new high of about US$ 55 per barrel [37] while the fuel oil price was about S$ 370 per tonne [22]. A scenario is studied by assuming that fuel oil and natural gas prices would double that of their current price while the price of solar PV modules would reduce to half of its current price. Under such circumstances, the cost of electricity from oil and natural gas would increase to about 25.23 ¢/kWh_e (@ 650 S$/tonne) and 19 ¢/$kWh_e$ (@17 S$/MMBTU), respectively whereas it would decrease to about 49 ¢/kWh_e (@ 6.5S$/$W_p$ and 5%interest rate) in the solar PV system. It can be seen that the cost of electricity from the solar PV system is now about 2 to 2.5 times higher than the oil/natural gas based power generation system. Solar PV based power generation can be shielded from oil price shocks when political vulnerabilities increase. Therefore, solar PV can be a good choice in the long run, especially in the light of GHG emission mitigation obligations and oil price shocks. The built-up areas in Singapore can be used effectively for the installation of solar PV systems and annually about 1000 GWh_e could be easily tapped[8]. However, it would require an installed capacity of about 1000 MW_p that would cost few billions of dollars. Still, it would be about 3% of the total electricity demand. Therefore, solar PV based power generation cannot be a complete substitute for oil/natural gas based power generation. However, efforts should be taken to explore all possible means to harness available solar radiation.

4.4. Fuel cells

From the efficiency of PEMFC, it can be concluded that fuel cell is not a good choice of power generation as the efficiency of a natural gas-fired combined cycle plant is 50%. However it should be borne in mind that fuel cell technologies are still at the infant stage of development compared to oil or natural gas-fired power plant technologies. Fuel cell technologies are benefiting from intense R&D [31,40–42] and therefore higher efficiencies are expected in the near future. The efficiency of PEMFC is projected to be 40% [39]. Under such a circumstance, its life cycle energy use and GWP would be 9.72 MJ_t/Wh_e and 586 g-CO_2/Wh_e, respectively. This would be better than the oil/ Orimulsion-fired steam turbine plants. However, they are still not comparable with the combined cycle plant. Nonetheless, for peak load applications, the fuel cell would be an energy efficient and environmental friendly option as gas turbines are currently used with an efficiency of less

[8]For example, total residential area in Singapore is about 73 km^2 [38]. If 10–15% of this area (rooftops/builtup) were be used for installation of solar PV system with a net efficiency of 7–8%, there would be a potential to generate about 1000 GWh_e annually.

than 40%. PEMFC would become a promising technology for peak load or premium quality power applications.

As far as the cost of fuel cell based power generation is concerned, ongoing technological innovations and advancement will allow PEMFC to enter the market at a very low cost, especially if it is adopted widely for the mass-market automobile sector. The projected cost for PEMFC is about S$ 1700 per kW [39]. If this cost can be realised, then the cost of electricity from natural gas based fuel cell technology would be 19.4 ¢/kWh$_e$ (@ 26% efficiency and S$ 8.7 per MMBTU). If both the efficiency and costs are realised, then the cost of electricity would be 15 ¢/kWh$_e$ (@ 40% efficiency and S$ 8.7 per MMBTU).

In the long-run, the solid oxide fuel cell (SOFC) could emerge as a competitive technology for power generation. For hybrid SOFC/gas turbine or SOFC/combined cycle systems, electrical conversion efficiencies are expected to be over 60% [40]. The US Department of Energy [41] has projected an electrical efficiency of 75% for advanced SOFC-based power plants and a cost target of US$ 400 per kW for SOFC under the Solid State Energy Conversion Alliance (SECA) program. Considering Singapore's interest in developing into a key fuel cell research hub [42], fuel cell technology could be considered for power generation in the future. Primary energy sources for fuel cells can include biomass-derived fuels that would further improve the fuel security for power generation.

5. Conclusions

LCA and LCCA models were developed and the life cycle energy, emissions and cost inventory was established for potential power generation technologies in Singapore. Power generation from clean/renewable power generation technologies are costlier than fossil fuel based power generation. However, their low environmental impacts can compensate for unfavourable economics if environmental externalities become an accepted paradigm in appraisal. Unfortunately, a reliable externality cost estimate is not yet established and the path to assessing externalities is still fraught with difficulties and uncertainties [43].

Considering limited potential for renewable energy sources in Singapore, power demand can be reduced through energy efficiency measures instead of catering to increasing power demand. Energy efficiency will be effective regardless of the future power supply scenario. However, it is not an easy task as there are many barriers to implementing energy-efficient technologies [19]. Making changes in traditional economic evaluation are important to the adoption of energy-efficient technologies on the demand side. If the costs of energy efficiency measures are compared with clean/renewable based power generation technologies instead of market electricity price, some transition barriers can be overcomed. Therefore, implementing policies with a mix of financial incentives and disincentives and direct investment in energy efficient technology would be an effective strategy for Singapore. Consumer education and supportive political/regulatory environment are vital in this context.

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